ACTA METALLURGICA SLOVACA
2026, VOL. 32, NO. 1, 49-53

RESEARCH PAPER

Bioremediation of cyanide in tailings wastewater – a mini review

Bagdaulet Kenzhaliyev [1], Nazerke Tolegenova [1], Kenzhegali Smailov [1], Balzhan Abdullaeva [2]*

[1] Institute of Metallurgy and Ore Beneficiation JSC, Satbayev University, Almaty, Kazakhstan
[2] Abai Kazakh National Pedagogical University, Almaty, Kazakhstan

*Corresponding author: n.tolegenova@satbayev.university, tel.: +747 455 71 04, Institute of Metallurgy and Ore Beneficiation JSC, Satbayev University, Shevchenko str., 29/133, 050010, Almaty, Kazakhstan

Received: 20.02.2026
Accepted: 03.03.2026

ABSTRACT

Cyanide-containing compounds are widespread in industrial wastewater from the mining and metallurgical industries. In aquatic environments, cyanide occurs predominantly as free cyanide (CN^-) and hydrogen cyanide (HCN), both of which are highly toxic due to their inhibition of cellular respiration. This mini-review provides a comparative analysis of the main physicochemical and biotechnological methods for cyanide removal from tailings wastewater, emphasizing the factors governing process performance and the constraints on industrial implementation. Based on a critical assessment of recent studies, chemical neutralization and oxidation technologies, as well as microbial cyanide biodegradation pathways, are discussed. The review shows that physicochemical methods can reliably reduce toxicity; however, they often require substantial reagent and energy inputs and may generate harsh reagents. Biological approaches using microorganisms and enzymatic systems can transform cyanide into less hazardous compounds, reducing the need for aggressive reagents and minimizing by-product formation. Although biological systems are generally slower than chemical oxidation, advances in strain development, process monitoring, and bioreactor technologies are enhancing the feasibility of biological and hybrid treatment trains for the sustainable treatment of tailings effluents.

Keywords: cyanide; bioremediation; tailings wastewater; microbial degradation; cyanotrophic microorganisms

INTRODUCTION

Cyanides are a group of organic and inorganic compounds that contain the functional group – C≡N; they are found in both natural and man-made systems [1-3]. In aquatic ecosystems, cyanide forms include the free CN^- ion, hydrogen cyanide (HCN), simple and complex metal salts, and fragments of organic molecules, including nitriles [4-5]. Cyanides are very reactive. Therefore, they readily form stable complexes with transition metals, which directly affect mining processes and the composition of effluents from tailings storage facilities [6].

Although cyanides are naturally involved in some biochemical processes, according to their toxicological characteristics, they are among the most dangerous pollutants in the environment [7-8]. The main danger is associated with the release of free CN^-. In solution, CN^- inhibits cellular respiration by strongly binding to metal-containing enzyme systems and disrupting important redox functions [9]. In toxicological studies, free cyanide and HCN are consistently listed as the most dangerous species [10]. Even low concentrations may be sufficient.

The origin of cyanide is not limited to anthropogenic factors. It is synthesized by bacteria, plants, and fungi; within cyanide-forming organisms, it often has a protective or regulatory function and is not always considered an external pollutant [11]. However, today the main load on ecosystems is largely determined by anthropogenic activity [12]. Gold and silver mining technologies using cyanide leaching make a significant contribution to this problem [13-14], [15-17]. As a result, cyanide species, together with heavy metals and other toxic substances, form large-scale ore residues. Long-term storage of cyanide waste in tailings wastewater and the occurrence of occasional emergency discharges indicate a persistent discrepancy between the scale of the risk and the effectiveness of existing management practices [18]. This requires technologies with an environmentally acceptable impact profile and that provide repeatable results. Physicochemical methods can quickly reduce toxicity but often have high operating costs; in addition, by-products formed during cleaning can lead to secondary contamination and weaken the long-term stability of solutions [19-21].

Against this background, interest in biodegradation has increased. In biological systems, microorganisms and their enzyme complexes play a leading role in detoxification: they convert toxic cyanide species into low-risk products through specific biotransformation pathways [22-24]. The purpose of this mini-review is to summarize and compare physicochemical and biotechnological approaches to cyanide removal from industrial tailings wastewater, systematize major microbial metabolic pathways, and discuss major limitations and scale-up issues related to industrial implementation. This work is a literature review that synthesises peer-reviewed publications and authoritative sources on cyanide speciation and treatment in industrial tailings effluents.

Current Methods for Cyanide Removal from Wastewater

In many legal systems, the maximum allowable concentrations of cyanide in receiving waters are strictly regulated. Therefore, industrial effluents should be treated with guaranteed reproducible removal efficiency to ensure compliance with discharge requirements [25-29]. In practice, it is this efficiency that often becomes the decisive limiting factor. This is especially acute in the mining industry: very large volumes of water containing cyanide need to be treated to regulatory levels.

Technology selection is site-specific and depends on the cyanide source and concentration, the overall wastewater chemistry, the feasibility of industrial-scale implementation, and economic viability. In addition, the species composition (speciation) of cyanide also plays a particularly important role. In the presence of heavy metals, cyanide forms stable metal-cyanide complexes that can remain in solution for extended periods, greatly complicating both detoxification and the extraction of target components.

Therefore, in industrial practice, the combined use of physical, chemical, and biological pathways in processing cyanide flows is widespread. Physicochemical schemes based on oxidation, complexation and stabilization [30] usually provide a rapid reduction in the concentration of free cyanide and weakly complex species. Many mining enterprises use these solutions; however, their use is often associated with high costs and the risk of secondary pollutant formation. In this regard, there is growing interest in biological purification as a technologically feasible alternative that relies on the activity of microbial communities and enzyme systems. Biodegradation can convert toxic cyanide species into low-risk products [31-32] (e.g. CO_2 and NH_3). In some cases, part of the substrate is used for assimilation and incorporated into biomass and strong oxidants are not introduced into the process. In general, these properties allow us to consider biological technologies as an option that meets the principles of environmentally responsible wastewater management involving cyanide.

Biological Methods for Cyanide Removal

Biological cyanide elimination harnesses the natural power of living systems, which either directly convert cyanide-containing compounds or seamlessly integrate them into metabolic pathways for complete and safe detoxification. This

https://doi.org/10.36547/ams.32.1.2272

approach fundamentally differs from and often surpasses traditional physicochemical methods. Chemical methods are usually aimed at the fastest and most complete decomposition of cyanide by reagent reactions and, in most cases, require strict technological conditions. On the other hand, biological technologies involve reducing concentrations to an environmentally acceptable level and directing carbon and nitrogen fluxes to low-toxicity products; at the same time, the wastewater matrix is not burdened by additional hazardous reagents.

In applied studies, two main areas of implementation are often discussed: phytoremediation and bacterial remediation. Phytoremediation uses plants and algae; some concepts also consider systems involving fungi and related microbial communities that support the retention and subsequent decontamination of cyanide species [33].

In plant metabolism, cyanide can act as an intermediate metabolite involved in the biosynthesis of some amino acids. At the same time, metal–cyanide complexes can interact with compounds in the rhizosphere - siderophores and other secondary metabolites formed by their accompanying microbiota - and contribute to their uptake, intracellular compartmentalization (including accumulation in the vacuole) and enzymatic transformations. In plant systems, β-cyanoalanine synthase and rhodanase are often referred to as the main detoxification enzymes [33-34]. Bacterial remediation relies on microbial metabolism to convert cyanide into low-toxicity products. Numerous microbial strains have been shown to efficiently oxidize or hydrolyze cyanide species, converting them into non-toxic end-products: CO_2, NH_3, amino acids, and a wide range of other low-molecular-weight metabolites. [35-36]. The most common species/taxa include Bacillus, Pseudomonas, Klebsiella, Alcaligenes and related groups, however, functional capacity is not evenly distributed even in these close relatives.

Therefore, when choosing a strategy, it is necessary to balance the external and internal constraints inherent in each approach. Phytoremediation develops slowly and is usually effective when cyanide concentrations are moderate; whereas in tailings wastewater, the pollutant load can be much higher. Bacterial systems are capable of employing more intensive mechanisms, but their efficiency often declines when stable metal–cyanide complexes dominate. The limitation is twofold: the high stability of the complex reduces the bioavailability of cyanide, and heavy metal ions released during partial destabilization inhibit cells and slow down conversion kinetics. Plant-based systems can sometimes more easily "lift" complex species and stabilize metal and cyanide species by intracellular binding molecules. For bacteria, the work profile largely depends on the specific strain; system behavior remains less predictable until targeted specialized cultures are selected [37].

In terms of use, cyanide biodegradation is sensitive to environmental parameters. The main determining factors include pH, temperature, nutrient availability, oxygen transport, and primary cyanide load. The stability of the process largely depends on adaptation: local communities must get used to the actual wastewater matrix, and in tailings wastewater, cyanide is usually not the only pollutant [38]. Bacterial systems generally tolerate a broader pH range, whereas plant- and fungal-based pathways often operate effectively only within a narrow pH window. In many studies, the optimal temperature for these processes lies within the mesophilic range, which can lower energy costs compared to physicochemical technologies that require harsh conditions. Microorganisms convert cyanide through multiple metabolic strategies, commonly categorized as degradation or assimilation pathways. Depending on the reactor design and wastewater composition, these pathways can operate under both aerobic and anaerobic conditions.

Several enzyme-mediated pathways have been described in bacteria, and the priority of a particular pathway can shift as pH, temperature, oxygen availability, culture medium conditions, and metal ion concentrations change. The overall result is the same: cyanide is converted to less harmful compounds, such as ammonia, amino acids, and carbon dioxide (CO_2). Amides and organic acids can be formed as intermediate or final metabolites. Alkali-resistant and alkaliphilic degraders are useful for treating wastewater from tailings ponds. Maintaining alkaline conditions stabilizes cyanide mainly in the CN^- form and inhibits the release (volatilization) of HCN. This improves process control and reduces the risk of HCN volatilization, thereby enhancing operational safety for personnel and the environment, incorporated into biomass and strong oxidants are not introduced into the process. Free cyanide and simple inorganic cyanides generally have the highest bioavailability. Microorganisms can oxidize them to CO_2 and NH_3 or subject them to hydrolysis transformations to form ammonia and low molecular weight intermediates. The dominant enzymatic pathway depends on the cyanide source and cultivation conditions, reflecting the metabolic versatility of cyanide-utilizing microorganisms. However, the situation is different with the metal-cyanide complexes inherent in tailings wastewater. Their stability depends on the coordinated metal, and biodegradation is further constrained by the toxicity of ions released during partial decomposition of the complex. To maintain activity in such conditions, microorganisms activate metal resistance mechanisms: binding isolation (sequestration) within the cell, enzymatic redox transformations, and active excretion (efflux). Biofilm formation also reduces the proportion of bioavailable metals, as it increases immobilization by forming a precipitate, trapping the metals in the extracellular matrix. Even within the same species, the ability to transform a complex cyanide can vary significantly between strains. In some cases, microorganisms do not directly degrade the complex; instead, they secrete chelating agents that mobilize cyanide, releasing CN^-, which then undergoes standard enzymatic transformations. This model clearly demonstrates the need for targeted selection of strains and the creation of specialized consortia for tailings wastewater with a heterogeneous chemical composition. Nitriles form a separate class of compounds containing cyanide [39]. Their microbial transformation often occurs either as a result of direct decomposition by nitrilases or through the nitrile hydratase → amidase cascade. Both aliphatic and aromatic nitriles can be transformed; however, the substrate specificity (specificity) is often obvious and must be taken into account when designing biological wastewater treatment systems [40]. The main microbial pathways involved in cyanide detoxification, their main enzymes, substrates, and products are summarized in **Table 1**.

Table 1 Microbial pathways of cyanide degradation and detoxification

Pathway	Main enzymes	Substrate	Main products	Notes
Hydrolytic	Cyanide hydratase, amidase, nitrilase	CN^- / nitriles	NH_3, organic acids	Most common
Reductive	Reductases	CN^-	CH_4, NH_3	Rare
Oxidative	Cyanide monooxygenase	CN^- / HCN	OCN^-	Detoxification
Sulfur-transfer	Rhodanese, 3-MST	CN^-	SCN^-	Important in plants and microbes

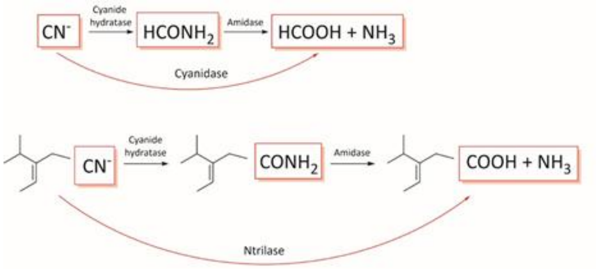

Fig. 1 Schematic overview of hydrolytic pathways in microbial degradation

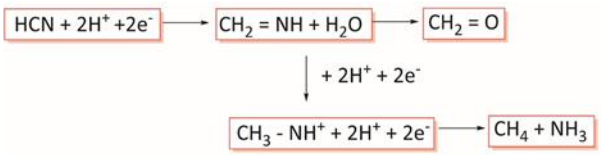

Fig. 2 Schematic overview of the reductive pathway in microbial degradation

Fig. 3 Oxidative pathway of cyanide degradation

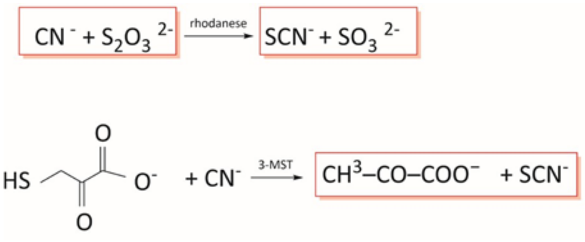

Fig. 4 Sulfur-transfer pathways of cyanide detoxification

Cyanide degradation proceeds via hydrolytic, reductive, oxidative, and sulfur-transfer pathways in microorganisms. **Figs. 1-4** outline the primary microbial metabolic pathways involved in cyanide degradation and detoxification. The **Fig. 1** highlights hydrolytic processes in cyanide bioremediation, where the cyanide ion (CN^-) is transformed by cyanide hydratase into formamide ($HCONH_2$), followed by amidase conversion to formic acid (HCOOH) and ammonia (NH_3); similarly, for nitriles (R-CN), cyanide hydratase produces an amide ($R\text{-}CONH_2$), which then undergoes amidase or direct nitrilase action to yield a carboxylic acid (R-COOH) and NH3. **Fig. 2** provides a schematic of the reductive pathway, in which hydrogen cyanide (HCN) undergoes sequential reduction to iminomethane ($CH_2{=}NH$) and formaldehyde ($CH_2{=}O$) through the addition of protons and electrons, with subsequent steps leading to methane (CH_4) and ammonia (NH_3) via a methylamine ($CH_3\text{-}NH_2$) intermediate. **Fig. 3** Illustrates the oxidative pathway mediated by cyanide monooxygenase activity, in which HCN or CN^- interacts with molecular oxygen (O_2) and NAD(P)H to form cyanate (OCN^-), $NAD(P)^+$, and water (H_2O), enabling cyanide oxidation in aerobic environments. Finally, **Fig. 4** details sulfur transfer mechanisms for cyanide detoxification, including rhodanese-catalyzed reaction of CN^- with thiosulfate ($S_2O_3^{2-}$) to generate thiocyanate (SCN^-) and sulfite (SO_3^{2-}), as well as the alternative process where 3-mercaptopyruvate sulfurtransferase (3-MST) shifts sulfur from mercaptopyruvate to CN^-, resulting in pyruvate and SCN^-.

Omics Approaches to the Study of Cyanide-Containing Environments

Omics technologies have established themselves as a key tool for creating a unified, holistic view of biological systems at several molecular levels. Genomics, metagenomics, transcriptomics, proteomics, and metabolomics enable simultaneous characterisation of microbial community composition, functional potential, and metabolic responses to toxic substances, including cyanide.

Objects exposed to cyanide particularly highlight the necessity of this approach. Many native microorganisms are challenging to cultivate under standard laboratory conditions; therefore, in situ community profiling (within the natural environment) is often essential rather than optional. Metagenomics provides a suitable high-throughput solution for this task: it evaluates taxonomic diversity, catalogs functional genes, identifies potential enzymatic pathways for cyanide conversion, and facilitates the targeted selection of taxa with bioremediation potential.

Studies comparing cyanide biodegradation "before/after" indicate that the transformation is not limited to a decrease in pollutant concentration. The internal organization of the community also changes, including the redistribution of functional roles. Intermediate metabolites and end products will displace the ecological balance and become crucial for engineering design of this process. For example, excessive amounts of free cyanide usually suppress secondary microbial functions that ensure system stability; as a result, the main functional guilds weaken and the overall resistance of the bioreactor (resilience) decreases.

Some works propose a systematic approach called cyanomics: it aims to combine omics and meta- omics strategies to explain how consortia neutralize cyanide and adapt to high stress conditions. Within this framework, genomic analyses reveal enzyme families and gene clusters involved in cyanide transformation and heavy-metal resistance. The practical significance of such data is obvious: they clarify the selection criteria for strains and consortia and reduce uncertainty when scaling biological purification schemes to the industrial level (scale-up).

Proteomics also complements another important methodological niche. If genomics describes the functional potential of a microbial community, proteomic profiling indicates exactly what action it performs under cyanide stress: it identifies expressed proteins directly involved in detoxification and the enzyme complexes that accumulate. Many studies have shown that during biodegradation, the concentrations of proteins involved in nitrogen metabolism, oxidative stress protective mechanisms, and universal stress response networks increase. Thus, proteomics provides a link between genetic potential and realized metabolic activity during cyanide stress. **Table 2** provides a brief overview of the latest omics studies aimed at cyanide bioremediation: it summarizes the microorganisms identified, the omics methods used, and the main results of each study.

Table 2 Summary of Recent Omics Studies on Cyanide Bioremediation

Study Reference	Microbes Found	Omics Techniques Used	Key Findings	References
Genomic Insights into Cyanide Biodegradation in Pseudomonas	Pseudomonas oleovorans (CECT 5344), P. fluorescens (NCIMB 11764), P. monteilii (BCN3), and another Pseudomonas spp.	Comparative genomics, phylogenomics (ANI, dDDH, GBDP), pan-genome analysis	nitC gene cluster for cyanide assimilation; cioAB, mqoAB for resistance; enables bioremediation.	[38-40]
Bacterial Tolerance and Detoxification of Cyanide, Arsenic and Heavy Metals	Pseudomonas pseudoalcaligenes CECT 5344; P. putida, Serratia marcescens, Burkholderia cepacia	Proteomics, meta-omics (metagenomics and proteogenomics discussed)	Cyanide assimilation via NitC and CioAB; oxidative stress, biofilm; tolerance to metal-cyanide for waste bioremediation.	[15, 22]
Metaproteomics Revealing Cyanide Bioremediators in Cassava Effluents	Bacillus, Pseudomonas, cyanotrophic consortia in cassava effluents	Metaproteomics	Tracked enzymes/microbes; hydrolytic/oxidative pathways; enzyme-based bioremediation for agro-wastes.	[21-22]
An Overview of Biological Cyanide Elimination from Tailing Wastewater	Cyanotrophic microbes (Pseudomonas, Bacillus, and microbial consortia)	Omics (genomics, metagenomics, synthetic biology)	Insights into pathways; design robust biocatalytic systems for wastewater treatment.	[28]

Optimization of Bacterial Cyanide Removal

The effectiveness of bacterial cyanide detoxification in tailings wastewater is determined by the balance between the physicochemical limitations of the medium and the biological potential of the strains used [35]. A primary distinction is between free cyanide (CN^-/HCN) and metal-cyanide complexes. Associated pollutants – heavy metals, thiocyanate, and phenolic compounds-have an additional effect on both the toxicity and availability of the substrate. The configuration and mode of operation of the reactor set the nature of the biocatalyst's interaction with this chemistry and determine whether the system will operate stably or fail when the composition fluctuates [41-42]. In practice, optimization usually rests on three goals: maintaining the viability of cells, maintaining the activity of the main enzyme detoxification components, and ensuring the stable operation of the system, even if the composition of the flux is variable.

The most direct control "mechanisms" - process conditions: pH, temperature and feed mode. Even strains separated from regions exposed to cyanide may show significant inhibition early in the process. Therefore, the addition of limited carbon and nitrogen sources is often employed to shorten the lag phase and enhance biomass resilience. However, such supplementation requires precise dosing: if easily metabolizable substrates predominate, cells preferentially utilize these substrates instead of cyanide, leading to a reduced elimination rate. pH plays a dual role by influencing CN^-/HCN speciation and modulating the catalytic activity of key detoxification enzymes. Temperature, in turn, reshapes reaction kinetics and cellular physiology. To reduce experimental costs, experimental design and statistical optimization are often used, and less labor-intensive factor combinations are chosen.

The second approach is the level of organization of the biocatalyst: monoculture or consortium. Real tailings wastewater does not consist only of CN^-; they are multicomponent mixtures, where mixed communities are often more effective than a single strain due to functional complementarity and cross – feeding of intermediate metabolites. Additional options include hybrid systems (e.g. bacterial-microalgae associations) and active sludge as a natural heterogeneous consortium. However, problems with compatibility, component stability, and controllability remain the main factors that prevent reliable prediction of the result.

The third area of optimization is the biocatalyst format: cells in suspension, immobilized cells or isolated enzymes. Immobilization of the carrier often increases stability: cells are "protected" from toxic effects to a certain extent, and biomass can be reused. However, the result depends on the choice of media, immobilization conditions and mass transfer restrictions. Immobilized enzymes can be kinetically more stable (repeatable) and are also important for the biosensorization of cyanide; however, with scaling, long-term performance issues inevitably arise in water where carrier cost, standardization and chemical composition are heterogeneous. Integrated schemes are also often described [42-43]: biological stages are combined with physical "support" processes and elements of plant-microbe systems to accelerate transformation and increase system resilience. Efficiency may increase, but such combinations also introduce additional risks, and they need to be openly evaluated. The most obvious example is the accumulation of toxic substances in biomass: if solid waste is not properly disposed of, it becomes a secondary pathway for pollution. From a practical point of view, the cascade hybrid approach looks promising: initially, plant-based sorbents provide retention, then microbial biotransformation leads to complete detoxification. In conclusion, the optimization of bacterial removal of cyanide from tailings wastewater is not limited to finding one "best" parameter. It requires coordinated management of pH, temperature and feed (input) water; reasonable choice between unicomponent and multicomponent systems; technically correct decision to use immobilized forms or enzyme modules; and, if necessary, integration with physical amplifiers or plant–microbe elements to maintain efficiency and stability in the case of variable input chemistry.

Limitations and Challenges of Biological Cyanide Removal

Although biological cyanide removal strategies have made it possible to reduce toxicity, their implementation at the industrial level is limited by a number of practical challenges. Cyanide imposes a high toxic burden on microbial systems, and the heavy metals and other co-occurring pollutants further amplify this inhibitory effect. Effluents from tailings ponds are chemically heterogeneous, temporally variable, and unpredictable. Such instability profoundly impacts microbial processes-even minor fluctuations in pH, temperature, or pollutant concentrations can compromise cell viability and inhibit the activity of detoxification enzymes. In addition, biological systems specializing in cyanide have their own limitations. Stable metal-cyanide complexes are often poorly biodegradable, which limits decontamination efficiency and complicates treatment process design. When scaling up, additional uncertainty arises, as results obtained in laboratory reactors are not always replicated under industrial conditions, where hydrodynamics, mass transfer, and episodic “shock” loads play a decisive role. Finally, today there is a limited number of standardized and Universal biotechnological solutions that can be used at various facilities without significant re-tuning. The combination of these factors narrows the scope of biological treatment, reduces operational stability and weakens the repeatability of results when working with real tailings wastewater.

Future Prospects and Research Directions

Further progress in the biological elimination of cyanide apparently relies not on individual biological stages, but on integrated technological architectures. The practical direction is clear: we need to combine methods.

Microbial consortia expand the functional spectrum and distribute the toxic load among participants; immobilization increases the stability of the biomass, allowing it to be reused; and hybrid process chains are effective in linking bioconversion to physicochemical steps, rapidly polishing wastewater and controlling process selectivity.

At the same time, the role of omics approaches and methods based on bioinformatic processing is increasing. They allow the identification of cyanide-resistant taxa, the description of the enzymes responsible for the main transformations, and the clarification of the mechanisms that regulate the expression of metabolic pathways under stress. This information justifies the selection of strains from an engineering point of view, the design of consortia and the optimization of a suitable "window" of operating parameters.

In recent years, interest in electro-biological configurations and new bioreactor designs that can work reliably on matrices with an unstable chemical composition, especially in tailings wastewater, has been growing. The main emphasis is on tolerance: to additional pollutants, to "shock" loads, and to ensure a predictable mode of operation regardless of fluctuations in the composition of the incoming stream.

The integration of these approaches enables the transition from laboratory demonstrations of biological cyanide degradation to widely applied industrial technologies.

CONCLUSION

Wastewater from tailings storage facilities, particularly those associated with gold mining, remains a persistent environmental and public health hazard due to the presence of cyanide and its associated chemical species. In industrial practice, physicochemical treatment methods remain predominant; however, their high energy and operational costs, as well as the potential formation of secondary pollutants over time, limit the environmental sustainability of such systems. Cyanide biodegradation offers a more environmentally compatible alternative. Numerous microorganisms can transform cyanide via various enzyme-mediated pathways, producing substantially less toxic products. This basis was reinforced by omics studies: genomic and metagenomic data on cyanide metabolism revealed processes in the natural environment (in situ) and revealed the role of complex microbial communities, including fractions that cannot be fully grown under standard laboratory conditions. Engineering progress also went hand-in-hand. Process optimization relies on consortia that complement each other functionally, immobilization strategies that allow for the stabilization and reuse of biomass, and integrated "production-microbe" configurations that increase resistance to inputs with complex chemical composition. Although these measures facilitate implementation, they do not fully overcome the primary “bottlenecks.” Resistance to fluctuations in wastewater composition, the duration of bioconversion, and the inherent challenges of scaling remain decisive factors. To make microbial cyanide biodegradation a sustainable option in production, future research needs to combine technological development with rigorous technical and economic evaluation, conduct validation in real tailings wastewater (not model solutions), and prioritize the reactor-level optimization that takes into account hydrodynamics, mass transfer, and episodic "shock" loads.

Acknowledgements: This research is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant № AP23488663).

REFERENCES

1. Alvillo-Rivera A, Garrido-Hoyos S, Buitrón G, Thangarasu-Sarasvathi P, Rosano-Ortega G: Journal of Materials Research and Technology, 12, 2021, 1418–1433. https://doi.org/10.1016/j.jmrt.2021.03.030

2. Dash RR, Gaur A, Balomajumder C: Journal of Hazardous Materials, 163, 2009, 1–11. https://doi.org/10.1016/j.jhazmat.2008.06.051
3. Kuyucak N, Akcil A: Minerals Engineering, 50–51, 2013, 13–29. https://doi.org/10.1016/j.mineng.2013.05.027
4. Logsdon MJ, Hagelstein K, Mudder T: The Management of Cyanide in Gold Extraction (ICME), Ottawa, Canada, 1999.
5. Mudder TI, Botz MM: European Journal of Mineral Processing and Environmental Protection, 4, 2004, 62–74.
6. Luque-Almagro VM, Huertas MJ, Martínez-Luque M, Moreno-Vivián C, Roldán MD, García-Gil LJ: Applied and Environmental Microbiology, 71(2), 2005, 940–947. https://doi.org/10.1128/AEM.71.2.940-947.2005
7. Hilson G, Monhemius AJ: Journal of Cleaner Production, 14(12–13), 2006, 1158–1167. https://doi.org/10.1016/j.jclepro.2004.09.005
8. Roldán MD, Olaya-Abril A, Sáez LP et al.: EMBO Reports, 22, 2021, e53720. https://doi.org/10.15252/embr.202153720
9. Ibrahim KK, Syed MA, Shukor MY, Ahmad SA: Biotropia, 22(2), 2015, 151–163. https://doi.org/10.11598/btb.2015.22.2.393
10. Sharma M, Akhter Y, Chatterjee S: World Journal of Microbiology and Biotechnology, 35, 2019, 70. https://doi.org/10.1007/s11274-019-2643-8
11. Bouabidi ZB, El-Naas MH, Zhang Z: Environmental Chemistry Letters, 17, 2019, 241–257. https://doi.org/10.1007/s10311-018-0795-7
12. Maniyam MN, Ibrahim AL, Cass AEG: Environmental Technology, 40(3), 2019, 386–398. https://doi.org/10.1080/09593330.2017.1393015
13. Koizhanova A, Kenzhaliyev B, Magomedov D, Kamalov E, Yerdenova M, Bakrayeva A, et al.: ChemEngineering, 7(3), 2023, 54. https://doi.org/10.3390/chemengineering7030054
14. Kenzhaliyev B, Surkova T, Yessimova D, Baltabekova Z, Abikak Y, Abdikerim B, et al.: ChemEngineering, 7(1), 2023, 14. https://doi.org/10.3390/chemengineering7010014
15. Jiang W, Lu Y, Feng Z, Yu H, Ma P, Zhu J et al.: Sustainability, 14(23), 2022, 15560. https://doi.org/10.3390/su142315560
16. Mekuto L, Ntwampe SKO, Mudumbi JBN: 3 Biotech, 8, 2018, 93. https://doi.org/10.1007/s13205-018-1124-3
17. Watts MP, Spurr LP, Lê Cao KA, Wick R, Banfield JF, Moreau JW: Water Research, 158, 2019, 106–117. https://doi.org/10.1016/j.watres.2019.02.058
18. Biełło KA, Cabello P, Rodríguez-Caballero G, Sáez LP, Luque-Almagro VM, Roldán MD, et al.: International Journal of Molecular Sciences, 24(8), 2023, 7232. https://doi.org/10.3390/ijms24087232
19. Offiong NAO, Edet JB, Shaibu SE, Akan NE, Atakpa EO, Sanganyado E et al.: Frontiers in Environmental Chemistry, 4, 2023, 1052697. https://doi.org/10.3389/fenvc.2023.1052697
20. Chettri D, Verma AK, Chirania M, Verma AK: Environmental Pollution, 363, 2024, 125297. https://doi.org/10.1016/j.envpol.2024.125297
21. Parsania S, Mohammadi P, Soudi MR: Iranian Journal of Microbiology, 13(52), 2024, 13–23. https://doi.org/10.22108/BJM.2024.136623.1521
22. Mendes HC, Kelbert M, Michels C, Soares HM: Journal of Water Process Engineering, 64, 2024, 105594. https://doi.org/10.1016/j.jwpe.2024.105594
23. Vaca-Escobar K, Arregui-Almeida D, Espinoza-Montero P: npj Clean Water, 7, 2024, 103. https://doi.org/10.1038/s41545-024-00392-9
24. Welman-Purchase MD, Castillo J, Gomez-Arias A, Matu A, Hansen RN: Science of the Total Environment, 906, 2024, 167174. https://doi.org/10.1016/j.scitotenv.2023.167174
25. AbdelMageed MF, ElRakaiby MT: World Journal of Microbiology and Biotechnology, 41, 2025, 26. https://doi.org/10.1007/s11274-024-04230-5
26. Alcoba YYD, Ferreira ML, Vullo DL: Clean Technologies and Environmental Policy, 27, 2025, 1693–1705. https://doi.org/10.1007/s10098-024-02916-w
27. Berkinbayeva A, Saulebekkyzy S, Kenzhaliyev B, Smailov K, Yessengaziyev A, Nurtazina N et al.: Metals, 15(10), 2025, 1162. https://doi.org/10.3390/met15101162
28. Berkinbayeva A, Kenzhaliyev B, Smailov K, Aimagambetov A, Kamenov B, Saulebekkyzy S et al.: Water Research X, 29, 2025, 100400. https://doi.org/10.1016/j.wroa.2025.100400
29. Olaya-Abril A, Biełło KA, Rodríguez-Caballero G, Cabello P, Sáez LP, Moreno-Vivián C et al.: Microbial Biotechnology, 17(1), 2024, e14399. https://doi.org/10.1111/1751-7915.14399
30. Kenzhaliyev B, Fischer D, Temirova S, Ultarakova A, Baltabekova Z, Bakhytuly N et al.: Processes, 13(4), 2025, 997. https://doi.org/10.3390/pr13040997
31. Kenzhaliyev, B., Koizhanova, A., Fischer, D., Magomedov D., Yerdenova M., Smailov K. et al.: Transition Metal Chemistry, 2025. https://doi.org/10.1007/s11243-025-00637-7
32. Abdulvaliev RA, Surkova TY, Baltabekova Z, Yessimova DM, Stachowicz M, Smailov KM et al.: Complex Use of Mineral Resources, 335(4), 2025, 50–58. https://doi.org/10.31643/2025/6445.39
33. Meher AK, Labhshetwar N, Pratap Reddy M, Bansiwal A: Journal of Environmental Science and Engineering, 59(1), 2017, 299–306. https://doi.org/10.47915/jese.2017.v59i01.004
34. Motsoeneng LG, Naidoo V, Mekuto L: Bioresource Technology Reports, 22, 2023, 101442. https://doi.org/10.1016/j.biteb.2023.101442
35. Sukurov B, Kvyatkovskiy S, Kozhakhmetov S, Semenova A, Dyussebekova M, Kvyatkovskaya M: Metals, 14(10), 2024, 1187. https://doi.org/10.3390/met14101187
36. Kenzhaliyev B, Kvyatkovskiy S, Kozhakhmetov S, Sukurov B, Dyussebekova M, Semenova A: Metals, 15(10), 2025, 1070. https://doi.org/10.3390/met15101070
37. Dyussebekova M, Kenzhaliyev B, Kvyatkovskiy S, Kozhakhmetov S, Semenova A, Sukurov B: Metals, 12(8), 2022, 1240. https://doi.org/10.3390/met12081240
38. Kim YM, Lee DS, Park C, Park D, Park JM: Water Research, 45(3), 2011, 1267–1279. https://doi.org/10.1016/j.watres.2010.10.003
39. Koizhanova A, Berkinbayeva A, Sedelnikova G, Kenzhaliyev B, Azlan M, Magomedov D et al.: Metalurgija, 60(3–4), 2021, 423– 426.
40. Watts MP, Gan HM, Peng LY, Lê Cao KA, Moreau JW: Environmental Science and Technology, 51(22), 2017, 13353–13362. https://doi.org/10.1021/acs.est.7b04152
41. Kenzhaliyev B, Surkova T, Berkinbayeva A, Baltabekova Z, Smailov K, Abikak Y, et al.: Metals, 15(3), 2025, 246. https://doi.org/10.3390/met15030246
42. Kenzhaliyev B, Berkinbayeva A, Smailov K, Baltabekova Z, Saulebekkyzy S, Tolegenova N et al.: Materials, 18(11), 2025, 2496. https://doi.org/10.3390/ma18112496
43. Vakilchap F, Mousavi SM, Baniasadi M et al.: Reviews in Environmental Science and Biotechnology, 19, 2020, 509–530. https://doi.org/10.1007/s11157-020-09544-y